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Validation and Optimization Testing of a Target Fueled Isotope Production Reactor

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ABSTRACT

This work outlines a testing and experiment plan for a proposed 2 MW open pool reactor fueled by Low Enriched Uranium (LEU) ^{99}Mo targets. Experiments and tests necessary to optimize reactor design and validate neutronic analyses are examined. The testing capabilities of Sandia National Laboratories are described. The importance of these tests and how the results help establish the safe operating envelope for a medical isotope production reactor is discussed. The experiments and tests will facilitate a focused and efficient licensing process necessary to bring on line a needed production reactor dedicated to supplying medical isotopes.

1. Introduction

A novel Low Enriched Uranium (LEU) fission based system for the production of ^{99}Mo using only targets is being investigated at Sandia National Laboratories (SNL). The conceptual design employs LEU oxide irradiation targets/fuel pins only; there is no separate driver core and target region. The quantity of ^{99}Mo produced is directly proportional to the power attainable in the target/fuel pins. Using this approach, ^{99}Mo can be produced in a cost-effective manner with little or no additional development of new techniques or processes and without uncertain licensing issues.

The concept uses target/fuel material to be similar to Light Water Reactor (LWR) fuel consisting of UO_2 enriched to less than 20% ^{235}U clad in Zircalloy or stainless steel [1]. The reactor system is in an open pool and relies on natural convective heating. The core consists of an annular target region surrounded by a Beryllium reflector. In the center of the core annulus is region for reactivity control elements. The effect of the Beryllium reflector and the center annulus is to flatten the flux profile of the core. The flat flux profile allows for equal burnup between target elements to maximize the amount of ^{99}Mo produced per MW of reactor power. The reactor is similar to university reactors in terms of power, hardware, and safety systems. Figure 1, is a rendering of the core design.

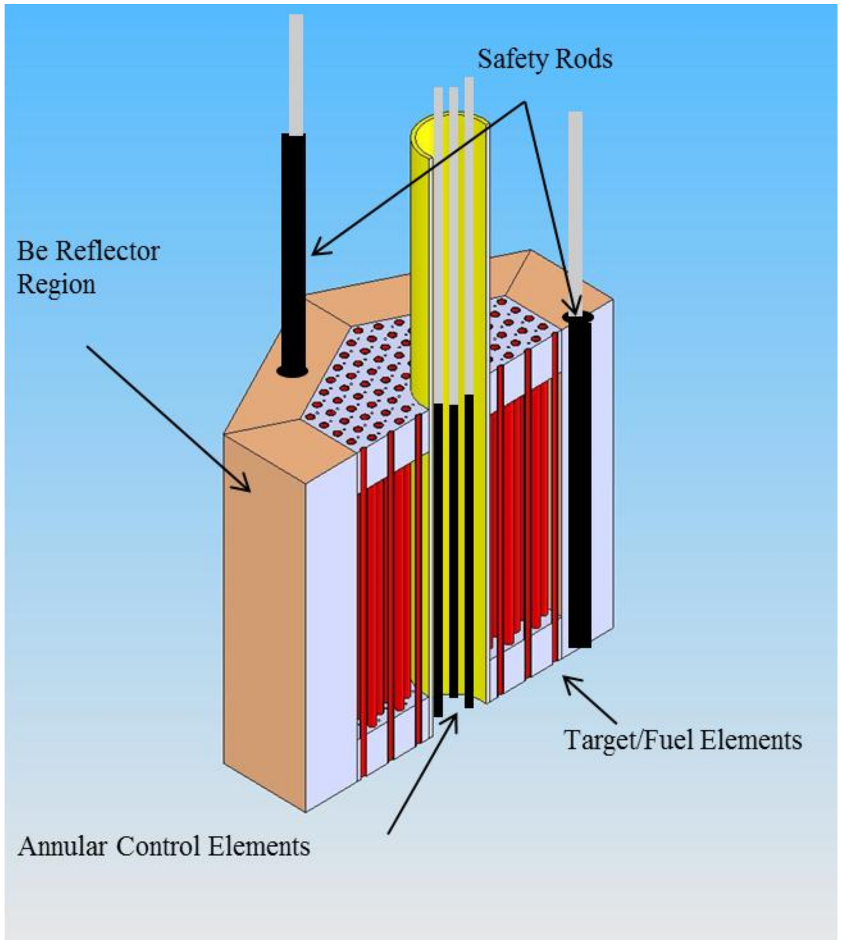

Figure 1. Conceptual Core Design of Target Fueled Production Reactor

2. Reactivity Feedback and Flux Profile Calculations

Design analyses were conducted to refine the core and fuel design and predict key core parameters. Using Monte Carlo[2] methods, parametric studies were conducted by varying core geometry, target dimensions, reflector materials, temperature and steady state reactor power. From these studies, elements of the design were down selected and the current concept was chosen. A critical design criterion for any reactor system is reactivity feedback. Reactivity feedback is the inherent changes to the nuclear and physical characteristics of a system that accompany variations in power levels. Negative feedback is necessary to help ensure the controllability and safe operation of the reactor. The parametric calculations show a strong relationship between negative feedback and fuel/target element pitch[3]. Figure 2 shows the results of the effect of element pitch on reactivity feedback for a core consisting of fuel/target elements 0.6 cm in diameter and 40 cm in length with an 8 cm Be reflector.

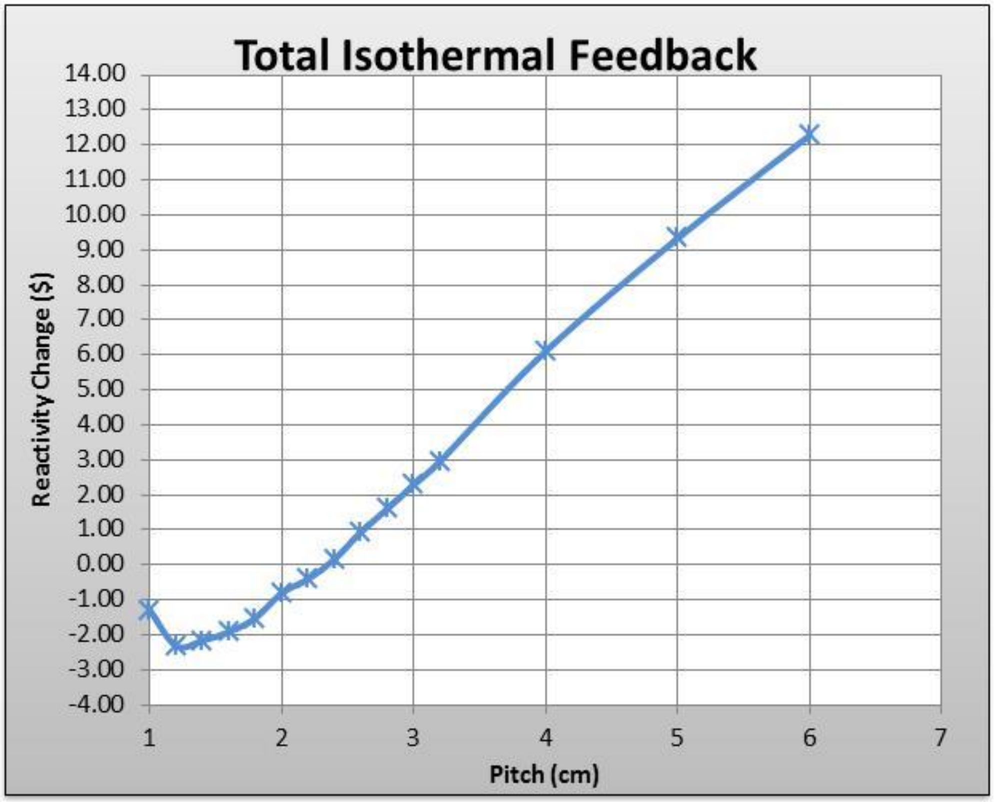

Figure 2. Calculated Isothermal Feedback as a Function of Pitch Size

Another important reactor parameter is the relative fission density. The relative fission density, both axially along the length of the fuel/target element and radially in its core position, is critical to optimizing the production of ^{99}Mo and understanding peak fuel/target element temperatures during operation.

Monte Carlo methods have a bias and uncertainty associated with the results. The uncertainty can typically be estimated, however, the bias is best measured. To support final design choices and establish the calculation bias, empirical testing of the core neutronic characteristics is desirable.

3. Approach to Critical Experiments

To validate the reactivity state and feedback calculations, experiments will be conducted at the Sandia Critical Experiment Facility (SCXF). One of the experimental capabilities at the SCXF is the Critical Experiment (CX) assembly. The CX assembly is a zero or low power system designed to collect nuclear criticality data on water moderated, low enriched, UO_2 critical configurations[4]. The assembly consists of a 1 m diameter tank that contains upper and lower grid plates that hold fuel elements. There is a second tank at a lower elevation then the core tank that contains the light water moderator. A neutron source (^{241}Am Be, or ^{252}Cf) is placed in the center or external to the core. The neutron source allows for subcritical multiplication factors (k_{eff}) to be measured. The fuel is loaded by hand when the core tank is empty, personnel exit the area and, moderator is pumped into the core tank. Safety and control rods are withdrawn and k_{eff} measurements are taken. The moderator is then drained and additional fuel is dry loaded and the processes is repeated until a critical condition is achieved. Figure 3 shows the CX core.

Figure 3. Sandia National Laboratories' Critical Experiment Assembly

The tests using the CX assembly will measure the reactivity feedback of three key design parameters; target/fuel pitch, reflector design and moderator temperature feedback coefficient. Three sets of grid plates of varying pitch will be fabricated and installed. The grid plates have a 1.50 cm, 2.00 cm and 2.25 cm pitch. Inverse multiplication experiments for each of these cores will be conducted to establish the number of target/fuel elements needed to achieve a critical state and measure the reactivity worth of each fuel/target element and the center control elements.

Different reflector configurations will also be investigated using the CX assembly. Two types of reflectors will be installed, a solid Be or BeO reflector and Be or BeO reflector elements in grid positions outside the active region of the core. The reflector elements consist of Be or BeO loaded in Zircalloy or stainless steel cladding and will be constructed in two diameters (1.5 cm and 2.0 cm). For a set pitch the thickness of the solid reflector will be varied and approach to critical experiments conducted. The size and number of reflector elements will also be varied and k_{eff} measurements taken.

The third series of approach to critical tests will examine the moderator temperature feedback coefficient of the various configurations. The water moderator is circulated through an external heater and the warm water is pumped into the assembly tank. The change in the number of target/fuel elements needed to go critical is an indication of the $\Delta\rho$ due to moderator temperature increase.

Based on the results of the inverse multiplication experiments, a final core configuration will be selected. For that selected configuration low power operations will be conducted. These low power (500W) operations will be run to establish the relative fission density across the core. After the low power operations, target/fuel elements will be removed and counted at a radiation meteorology laboratory collocated with the SCFX. Radiation metrology measurements of fission products will be taken of selected fuel/target elements in each row at the same axial position (core centerline). These measurements will provide the relative radial fission density. Selected elements at various radial row positions will be measured along the axis of active fuel region to give the axial fission density. Also, during the low power runs, various dosimetry packages will be deployed. The dosimetry will consist of bare and cadmium encapsulated nickel and gold. These activation foils will be counted and the neutron energy spectrum will be estimated for the core.

The various tests at the SCFX will help establish key operating parameters and limits. The k_{eff} measurements will determine core excess reactivity and shutdown worth of safety rods. Excess reactivity measurements establish the bounds of reactivity that could be added to the system during reactor transient accidents. This is an important parameter for licensing and limiting core damage in the unlikely event of an reactor transient accident. The maximum reactivity worth of the safety rods and control rods establish the shutdown margin of the system. The shutdown margin is the reactivity necessary to ensure the reactor can be made subcritical from all normal operations and credible accident conditions. Shutdown margin must be sufficient to overcome the reactivity effects of fission product poisons, such as Samarium and Xeon. The shutdown margin must also be sufficient to overcome negative reactivity feedback that would be a factor at power such as Doppler cross-section broadening of ^{238}U and the density of the water moderator. The experiments on the CX assembly would not be conducted at temperatures where these feedback mechanisms are significant, but they would determine safety and control rod reactivity. These parameters would be established in the technical specifications of the reactor system and calculated and verified periodically during the operational life of the system.

4. Thermo-Hydraulic Tests

The proposed design is not pressurized as it sits in an open pool. Thus, the coolability of the target/fuel elements is one of the limiting factors for total system power. The pool volume, along with standard heat exchangers and cooling towers, are more than sufficient to reject the heat generated by a 2 MW system. The limiting factor is the heat flux from the fuel across the cladding to the coolant. Adequate heat rejection is dependent upon limiting the boiling to nucleate boiling at the cladding coolant interface (i.e. the absence of a steam-filled void at the interface). The heat flux, at which a system departs from a nucleate boiling condition, is known as the Minimum Critical Heat Flux (MCHF). When the MCHF condition is achieved, the heat transfer to the coolant becomes inefficient; fuel and cladding temperatures will increase rapidly and cladding may fail due to the dramatic reduction in element cooling.

Confirming the calculated MCHF can be supported experimentally outside of a reactor core. A tri-lattice of simulated (i.e. no fissile material) target/fuel elements will be setup in a deep (~6 m) pool. Sandia National Laboratories has several pools available for such tests. The elements will be electrically heated to the range of peak element power calculated to occur during normal and accident conditions. The average target/fuel element power is anticipated to be 10 kW per element up to a maximum of 38 kW. Based on calculations this would equate to a UO_2 matrix temperature of about 1200º C. The coolant channel inlet temperature will be controlled to simulate a coolant loop return and the coolant channel outlet temperature will be measured. These tests will help confirm the MCHF for the system. This will be translated into reactor power limits to ensure cladding integrity factoring in an adequate safety margin.

5. Transient Target/Fuel Tests

The final series of tests involve subjecting driving the target/fuel elements to ramp reactivity addition tests. These tests require a research reactor capable of power levels similar to the operating range of the isotope production reactor. The research reactor must also be capable of doing transient tests where power levels are increased very rapidly. Sandia National Laboratories' Annular Core Research Reactor (ACRR) is licensed up to 4 MW steady state operation and capable of short pulse transients[5]. The ACRR is an open pool reactor system based on a TRIGA design. The reactor uses UO_2-BeO ceramic fuel pellets in stainless steel cladding. It has a large dry irradiation cavity in the center of the core. Figure 4 shows the ACRR core in its tank.

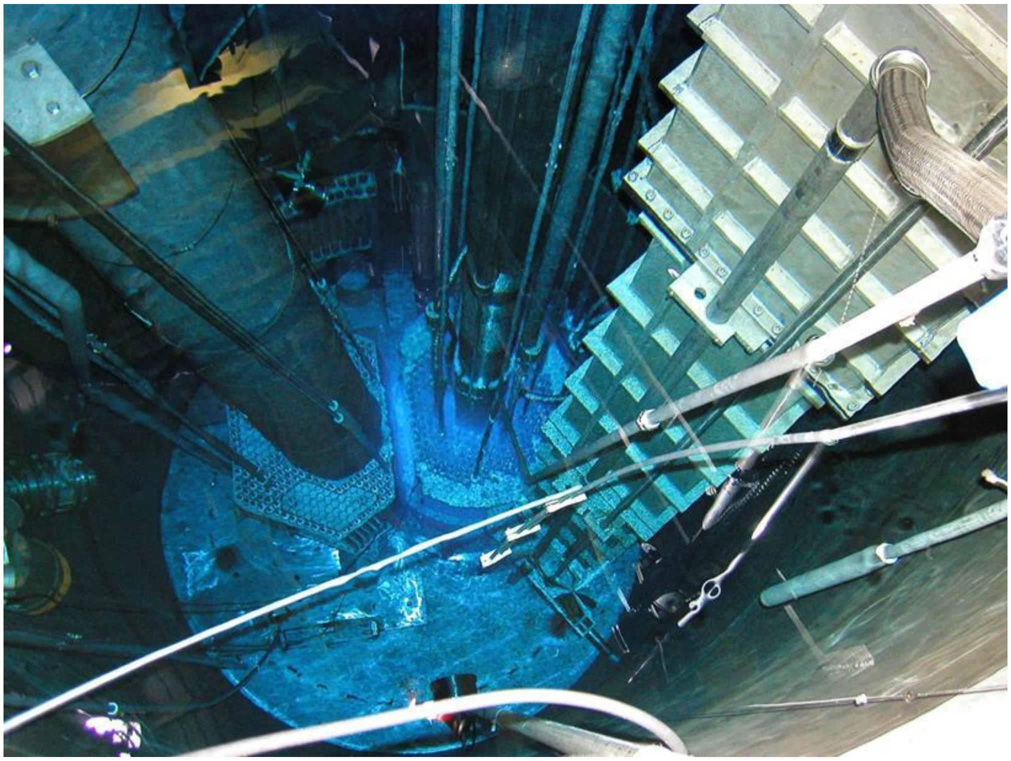

Figure 4. The Annular Core Research Reactor at Sandia National Laboratories

For licensing of the isotope production system, target/fuel response during accident conditions must be estimated. The most significant accident of consequence in this type of reactor is a reactor transient. A transient is the rapid increase of reactivity in the system causing rapid fuel heating. The reactivity is added so quickly that the thermal response of the system lags and is ineffective at dissipating energy deposited into the target/fuel matrix. As a result, target/fuel material may melt, and/or fission product or backfill gases may increase the internal element pressure to the point of hoop stress failure of the clad.

The ACRR has the capability to drive fuel elements to failure by rapidly adding reactivity. Amongst the 12 safety and control elements at the ACRR, there are three elements that can be pneumatically ejected from the core. The result is a rapid transient or pulse. The ACRR is capable of pulses that exceed 30,000 MW in peak power with a full-width half maximum pulse width of 70 μsec. Preparing for target/fuel failure tests would be involved and take many months. Special experiment containment would need to be designed and tested to ensure that the target/fuel elements subjected to the transient are safely contained. Instrumentation would need to be designed into the experiment package so that data on pressure and temperature could be collected. Radiation dosimetry would also need to be used so that neutron flux and energy spectrum could be characterized.

Transient tests would be expensive and only undertaken if the regulator required them as part of the license application. It would be argued that since similar experiments on Light Water Reactor fuel have been conducted in the past, no new transient or fuel failure tests would be required.

6. Conclusions

A thorough and planned testing schedule for a dedicated medical isotope production reactor can be executed at Sandia National Laboratories. The tests laid out in this work will validate design calculations, optimize the final design choices and support the licensing process. Approach to critical and low power testing will help establish key operating parameters of the reactor system. Out of core thermo-hydraulic tests will help establish reactor power limits. Transient tests can be conducted at Sandia's research reactor. The test plan outlined here can support an efficient and relatively inexpensive licensing approach for a low power, inherently safe, dedicated reactor for the production of medical isotopes.

7. Acknowledgements

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